VARIATIONS IN AIR QUALITY OF NEW OHIO DAIRY FACILITIES WITH NATURAL VENTILATION SYSTEMS

L. Y. Zhao, M. F. Brugger, R. B. Manuzon, G. Arnold, E. Imerman

ABSTRACT. *As dairy operations evolve towards larger, concentrated facilities, air quality on and around the dairy farms becomes a concern. Data on air quality in and around large dairy facilities are insufficient and therefore very much needed. In this study, preliminary data on air quality spatial distribution and temporal variations on two new large dairy facilities with naturally ventilated free stall barns and outside manure storage were collected. Concentration of hydrogen sulfide (H_2S) and ammonia (NH_3) at 12 to 14 locations on each farm were measured in three seasons using portable gas analyzers. Odor samples were collected at odor sources, upwind and downwind locations. Dust was measured using a portable dust mass concentration meter. Gas levels inside the dairy buildings at one leeward location were continuously monitored for three days in two seasons. In addition, indoor and outdoor temperature, relative humidity, and air velocity were measured to determine effects of these parameters on air quality.*

The study found that manure storage ponds have the most effect on air quality during warm and hot seasons. Variations of air quality inside the dairy building were insignificant. Inside the dairy buildings, the average dust mass concentrations range from 0.9 to 1.5 mg m^{-3}; ammonia 1.4 to 3 ppm, hydrogen sulfide 2 to 32 ppb; and odor concentration 90 to 140 OU m^{-3}. However at the downwind berm of the manure storage ponds, odor concentration reached 1256 OU/m^3 during the hot weather months. Weather conditions also affected the outdoor dispersion of air emissions. Most of the time, gas levels at 152 m downwind of the barn and manure storage were similar to upwind levels, but on hot and windy days these levels reached a point high enough to raise concerns. Inside the building, the hydrogen sulfide concentrations were not significantly different from hour to hour within a day or from day to day within a season. Although daily variation of mean ammonia concentrations were significantly different, hourly mean ammonia concentrations were not significantly different between morning hours and afternoon hours within any given day.

Keywords. *Dairy, Air quality, Dust, Odor, Carbon dioxide, Ammonia, Hydrogen sulfide.*

Air quality within dairy barns and air emissions from dairy operations, especially the new large free-stall dairy facilities, are receiving increased interest. Neighbor complaints and lawsuits are originating based on odor and gas emissions from dairy operations. However, there is limited scientifically based information on air quality, i.e. odor, gas, and particulate matter (PM) concentrations associated with dairy operations.

Most previous research has focused on determining emission rates from buildings and/or manure storages; therefore air quality of dairy facilities has been studied only at limited locations within the facility. A more comprehensive understanding of air quality spatial distribution in dairy buildings is important to maintain cow health and to determine representative air sampling locations for air emission studies. Air quality spatial distribution on the dairy farm will also help to expand understanding of air emission dispersion and the impacts of the dairy facilities on ambient air quality. This research viewed the dairy facility as a system and comprehensively studied air quality of two new larger dairy farms and its potential impacts on neighboring communities.

Ammonia emissions from dairy operations have been studied more than other gases or odors. Arogo et al. (2003) reported that dairy ammonia emission factors ranged from 14.8 to 23.5 kg NH_3 yr^{-1} per animal and mean ammonia concentrations in cattle houses were lower than 8 ppm, with most of the data coming from European countries. Mutlu et al. (2004) reported ammonia emission and concentrations from a Texas free-stall dairy barn which flushes four times per day at 36.4 to 23.3 ppm: from lagoon #1 at 2.0 to 0.5 ppm, and from lagoon #2 at 0.4 to 0.3 ppm. Schmidt et al. (2002) reported average ammonia concentration in a 550-cow free-stall barn with scraped alleys of 240 ppb in winter and 1140 ppb in summer. The range was 40 to 4380 ppb in the winter and 310 to 4920 ppb in the summer. Significant variations in ammonia concentration in dairy buildings exist due to facility types, weather conditions, and geographic location.

Hydrogen sulfide is a toxic gas and has potential to cause health problems if the concentration becomes too high. Wood et al. (2001) reported an emission rate of 3.6 mg h^{-1} m^{-2} from

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a dairy free-stall operation. Schmidt et al. (2002) reported levels of 0 and 2ppb in the winter and a range of 0 to 15 ppb in the summer for a 550-cow free-stall barn with scraped alleys. Bicudo et al. (2003) reported hydrogen sulfide concentrations of 0.02 to 5.7 ppb downwind of a free-stall barn and 0.9 to 20 ppb around a dairy manure storage pond. H_2S concentrations at the property line are regulated in some states such as Minnesota, which has a property line limit of 30 ppb.

Dust emissions from a European study, as reported by Takai et al. (1998), ranged from 21 to 338 mg h^{-1} per 500 kg live weight for inhalable dust and 13 to 54 mg $h^{-1}AU^{-1}$ for respirable emissions. Schmidt et al. (2002) reported that inhalable dust concentrations varied from 0.28 to 0.88 mg m^{-3} from winter to summer at one Minnesota dairy farm.

Odors cause the most complaints. Wood et al. (2001) reported an emission rate of 1.3 OU s^{-1} m^{-2}. Schmidt et al. (2002) reported a summertime odor concentration of 280 OU/m^3 for a 550-cow free-stall barn with scraped alleys. Bicudo et al. (2003) reported odor emissions from a dairy manure storage pond at 7 to 10 OU s^{-1} m^{-2} and from the barn at 2 to 3 OU s^{-1} m^{-2}.

This research project addressed the limited data for larger free-stall dairy barns with manure scraping systems and outside manure storages. This project comprehensively studied both spatial and temporal air quality variations on two Ohio dairy farms in order to assess environmental exposure risks to farmers, cows, and neighbors, and also to address possible mitigation needs.

Materials and Methods

Aerial pollutants consist of a variety of gases (mostly ammonia, hydrogen sulfide, methane, and carbon dioxide), particulate matter (dust and vapor aerosol), odor, and Volatile Organic Compounds (VOCs). The EPA has identified ammonia, hydrogen sulfide, dust, and some VOCs as the most hazardous substances emitted from animal production operations. Odor is the prominent source of neighbor complaint regarding such animal production facilities. Therefore, at two larger dairy facilities, air quality parameters including ammonia, hydrogen sulfide, carbon dioxide, dust, and odor concentrations were measured comprehensively over three seasons.

Air quality is affected by weather conditions, animal facilities, and management practices. Therefore, weather data and indoor temperature, relative humidity, and air velocity were also measured. Additionally, manure management practices, dairy cattle number, and milk production data were acquired from the producers.

Dairy Facilities

Two farms with recently built free-stall large dairy facilities were studied in this project.

In 2003, a farm with a 675-cow, 6-row free-stall dairy barn (#1) located in Northwest Ohio was monitored. The dairy building was 122 m (400 ft) long, 33 m (108 ft) wide, and 3.5 m (12 ft) high at the side wall (fig. 1). It is a modern dairy barn with a 6-m wide center drive-through feed alley. More detailed layout and dimensions of the dairy buildings are illustrated in figure 1. Natural ventilation is provided by 3.5-m (12-ft) high sidewall curtains, 0.609-m (24-in.) wide open ridge, and overhead doors at the end of service and feed alleys. The building has cooling fans above the free stalls and water misters along the drive-through feed alley line. The free stalls are sand bedded.

Alley scrapers with timer control bring the manure to a center cross alley where a gutter cleaner carries the manure to a solids/sand settling basin. The liquids flow from the settling basin to a 6 million-gallon earthen manure storage basin. The sand settling basin is emptied several times a year. The large manure storage is emptied at least once a year. Before emptying the storage, the manure is agitated with a tractor-powered chopper/agitator unit. Once agitated, the manure is pumped through soft hose to a tractor-pulled injection system which injects the manure under the surface.

Both farms use a total mixed ration with the corn and haylage stored in bunker silos adjacent to the barn. Dry grains are stored in commodity storages near the bunker silos. The cows are fed twice a day with the feed being pushed up several times during the day.

A milking center and dry cow area are adjacent to the free-stall barn. About 85% of the cows are lactating at any time. The cows are milked three times per day. The average milk production is 36 kg d^{-1} (80 lb d^{-1}). The barn had all the ventilation openings working during the data collection.

In 2004, at a central Ohio location, a separate 675-cow, 6-row free-stall barn (#2) with adjacent manure storage and natural ventilation was also studied. The two dairy facilities were designed by the same developer and therefore have very similar layouts as well as management practices.

Experimental Design and Sampling Procedures

Spatial measurements were made in March, June, and August of 2003 on Farm 1. In March, June, and August of 2004, measurements were made on Farm 2. The March, June, and August dates represent cool, warm, and hot weather conditions, respectively. In 2004, three-day continuous gas concentrations and indoor environment data were collected at a leeward location in the dairy building of Farm 2.

For each dairy facility, spatial measurements were made at 12 locations (fig. 2). One location was upwind of the farm, then there were locations at eight points within the building, and finally there were three outdoor locations: at the manure storage pond and 61 or 152 m (200 or 500 ft) downwind of the barn. The locations within the barn were uniformly selected to give an indication of spatial variation. At alley locations where people were the main occupants, sensors were located to measure conditions at human head height. Where cows were the main occupants, sensors were set up at cow head height: standing head height at alley locations and lying head height at stall locations.

For all measurements, a minimum of three data values was recorded at each location. Two or three gas tube measurements were made for ammonia, carbon dioxide, and hydrogen sulfide, which at the same time served as a check against the electronic equipment. The spatial data was collected at the points outside of the building before the points inside the building.

Odor concentration measurements were taken upwind of the barn, at the farmer's residence yard, inside the building, near the manure holding pond, and 152 m (500 ft) from the barn and manure storage in the downwind direction. The upwind location represents a clean place, which is assumed

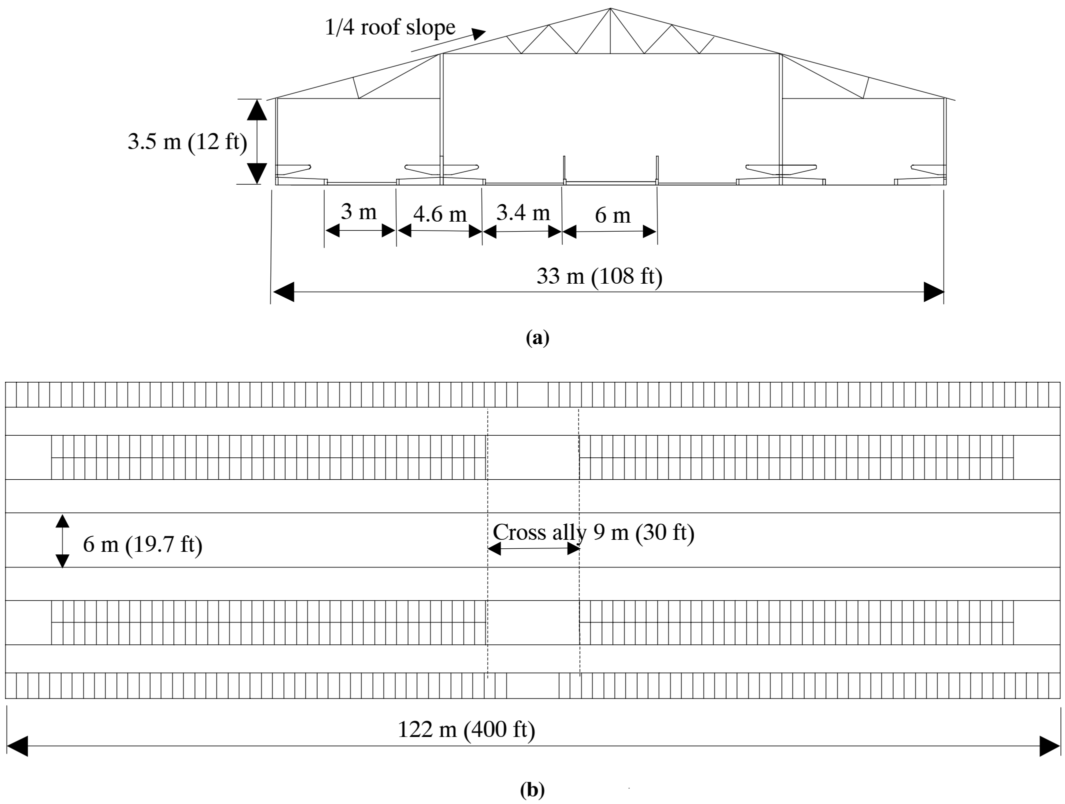

Figure 1. Schematic of (a) the floor plan and (b) the cross section of a modern 6-row free-stall barn with a center drive through feed alley, 3.23-m (11-ft) side curtains, and 0.588-m (2-ft) open ridge.

free of air emissions from the dairy facilities. The residence yard measurement is used to assess the level of exposure to the farmer's family. Inside of the dairy barn and near the manure holding pond are considered air emission sources. Air quality at 152-m downwind location represents the neighbors' exposure.

Measurement Methods

The air-monitoring instruments used for these projects were portable electronic instrument and gas detector tubes. The electronic instruments were the primary monitors. The gas detector tubes were used during the spatial monitoring as a check against the equipment. Before each data collection period, the equipment was checked in the laboratory. All equipment had received recent factory service and calibra-

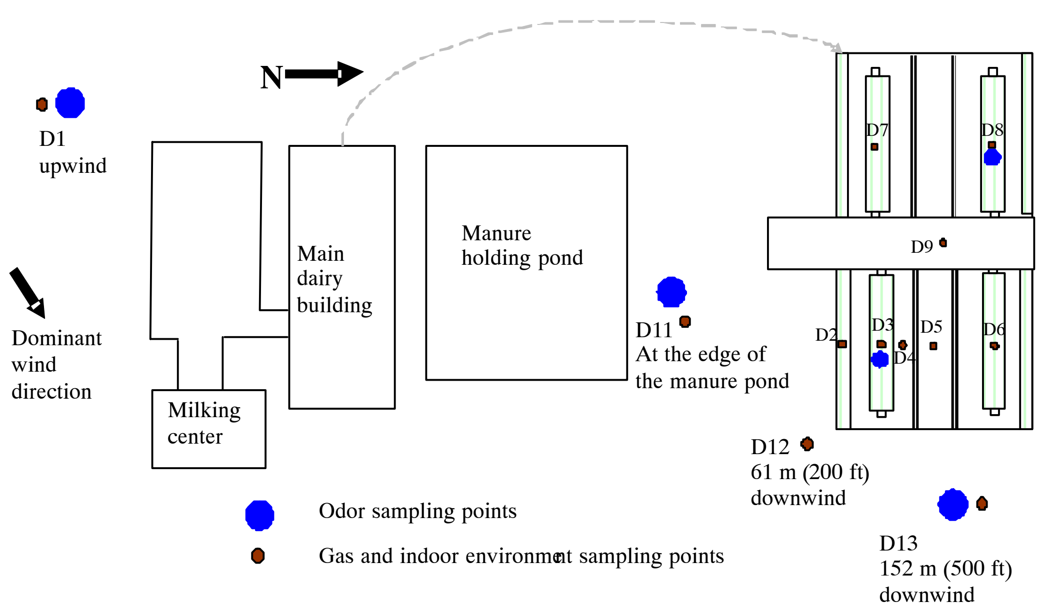

Figure 2. Farm layout and air quality measurement locations of the dairy farm.

tion before the start of the data collection season. For the temporal collection period, the equipment was set up on day one and picked up on day four with no intermediate visits. Unfortunately, some temporal data is missing because of malfunctions with the instrumentation. The sampling rates for quasi-continuous gas measurements were 2, 15, and 15 min for CO_2, H_2S, and NH_3 measurement, respectively.

Gas Measurement

Hydrogen sulfide was measured using a Jerome H_2S analyzer (631-X, Arizona Instruments, Tempe, Ariz.). The measurement range of 0.003 ppm (1 ppb) to 50 ppm makes it appropriate for monitoring the levels typical of livestock facilities. The resolution is 0.001 ppm. The accuracy is about 6% of measurement values.

Ammonia concentration was measured using a Single Point Air Monitor (MDA Scientific Single Point Monitor, 970889, Zellweger Analytics, Lincolnshire, Ill.). The SPM has a "chem-cassette" detection system and microprocessor control to achieve optimum detection speed, accuracy, and specificity. The SPM is equipped with ChemKey function for ammonia detection of 0 to 30 ppm at 0.5-ppm resolution. The SPM has data output and can work with an external data logger.

Carbon dioxide was measured with TSI IAQ-CALC™ Meter (IAQ Calc-8762, TSI Inc., Shoreview, Minn.). The IAQ meter uses a dual-wavelength NDIR non-dispersive infrared sensor. The measurement range is from 0 to 5000 ppm. The accuracy is ±3.0% of reading or ±50 ppm, whichever is greater. The resolution is 1 ppm.

As a check of the electronic gas analyzers (hydrogen sulfide, ammonia, and carbon dioxide), concentrations were measured at each location with appropriate colorimetric sampling tubes (Matheson-Kitagawa Precision Gas Detector Tubes, Matheson Tri-Gas Inc., Montgomeryville, Pa.) A Matheson-Kitagawa (model 8014-400A) hand-held pump was used with the appropriate tubes following the recommended procedures to measure the gas concentrations. Typically two readings were taken. A third reading was taken if the first two showed a significant difference. When there was a discrepancy between tube and equipment readings, the equipment was checked and another set of readings was taken. The accuracy of the tubes is 5% to 15%.

Dust Measurement

Dust mass concentrations were measured using a MicroDust Pro 880nm Aerosol Monitoring System (Casella USA, Amherst, N.H.). The MicroDust Pro is a survey instrument for the assessment of particulate concentration in mg/m^3. It is portable and suitable for real-time measurement of fixed sites. It is based upon forward light scattering techniques. The measurement range can be from 0.001 to 2.5 mg m^{-3}, 0.01 to 25 mg m^{-3}, 0.1 to 250 mg m^{-3}, or 1 to 2500 mg m^{-3}. The equipment is calibrated with the specific dust using gravimetric sampling method.

Dust size distribution was measured using Climet CI-500 Laser Particle Counter (Climet Instruments Co., Redlands, Calif.). The Climet CI-500 is a laser diode-based particle counter. The particles are sized and counted in six size channels: >0.3, >0.5, >1.5, >5, >10, and >25 microns. The measurement limit is 1,000,000 particles/ft^3. It has an iso-kinetic sampling head and extended sampling tubes for accurate dust sampling. -

Odor Measurement

Dynamic forced-choice Olfactometry method, the most commonly accepted technology, was used for odor measurement. The air samples were taken with an SKC Vac-U-Chamber, 10-L Tedlar air sampling bags equipped with a polypropylene fitting, and a Buck I.H. Pump (SKC Inc., Eighty Four, Pa.). The air samples were sent to the Purdue Agricultural Air Quality Laboratory at Purdue University for dilution threshold (OU analysis) values within 30 h of collection. At Purdue, the air samples were analyzed by a dynamic olfactometer (AC'SCENT International Olfactometer, St. Croix Sensory, Inc., Minn.) using eight trained panelists.

Indoor Environment and Weather Condition Measurement

Temperature and relative humidity were measured using a TSI IAQ-multimeter (model IAQ-8762, TSI Inc., Shoreview, Minn.). The temperature sensor has a measurement range of 0 to 60°C (32°F to 140°F), an accuracy of ±0.56°C (±1.0°F), and a resolution of 0.056°C (1°F). The relative humidity sensor has a measurement range of 5% to 95%, an accuracy of ±2.0%, and a resolution of 0.1%. The air velocity was measured using a Velocicalc Meter (model 8384, TSI Inc., Shoreview, Minn.). The meter has a measurement range of 0 to 9999 fpm and 3% measurement error. The Velocicalc meter, IAQ meter, and a portable weather station (Cole Parmer catalog number C-99756-17) were used to monitor weather temperature, relative humidity, and wind speed conditions on the farm. Weather data maintained by adjacent Ohio weather stations were used as reference.

Data Analysis

General descriptive statistical analysis was conducted. By summarizing pollutant concentrations at 14 locations of a farm, pollutant concentration distribution on a farm is revealed. The values were also compared to the standard exposure levels documented by NIOSH to identify the potential health risks.

In addition, the analyses of variance were performed using SAS® 9.1 (SAS Inc., Cary, N.C.) on the continuous air quality data and on discrete air quality data in order to examine significant air quality variations in seasons, days, and hours. The confidence level used was 0.05.

Results and Discussion

Climatic Data

Table 1 shows the weather conditions around the farms on the days when air quality surveys were conducted. In March of 2003 and 2004, the temperatures were warmer and more humid than usual and as a result did not reflect the desired winter weather conditions. In June of 2003, the test day was windy. In August of 2003, the weather was a typical hot day. In 2004, the average temperatures were 54°F, 80°F, and 67°F, respectively, for March, June, and August measurement days. Therefore, the resulted test days did not truly

Table 1. Weather conditions around the dairy farms during the air quality survey.

Weather Conditions	Dairy Farm 1 (2003) March	June	August	Dairy Farm 2 (2004) March	June	August
Daily average temperature (°F) (low-high)	52 (48–57)	66 (57–77)	77 (68–87)	54 (46–61)	80 (71–89)	67 (57–77)
Daily average relative humidity (%) (low-high)	75 (58–96)	72 (57–93)	82 (56–97)	84(62–100)	72 (52–91)	72(52–93)
Wind speed (mph) (low-high)	0–9	0–22.7	0–6	0–7	0–10	0–12

reflect cool, mild, and hot conditions. Since the dates had to be coordinated with the dairymen and the Air Quality Laboratory in advance, selecting dates for optimum climatic conditions was very challenging.

Air Quality Spatial Distribution Inside the Dairy Barns

Table 2 shows the mean and standard deviations of the indoor air quality data of eight locations inside the dairy buildings at locations designated in figure 2. The overall low air pollutant concentration levels and relatively small standard deviations indicate the limited spatial variations in air quality inside the dairy barn. The average ammonia concentration ranged from 0.3 to 3.0 ppm and the hydrogen sulfide concentration 2 to 31 ppb, odor about 100 OU m^{-3}, carbon dioxide 349 to 513 ppm, and total suspended particle concentration 0.16 to 1.5 mg m^{-3}. Air quality inside new large dairy buildings is acceptable in comparison with OSHA and NIOSH indoor air quality standards, which are listed in table 3 (Donham et al., 2002). The data for each point did not indicate a definite pattern with respect to the wind direction. Looking at both years, the spatial variations in air quality, as indicated by the low air pollutant concentrations and small standard deviations, were small. The temperature and relative humidity within the barn were similar to the outside conditions and did not vary significantly among the locations. However, air velocities at the different locations varied largely.

To compare air quality inside the dairy facilities at different seasons, Pairwise means comparison statistical analysis were conducted using LSD procedure (least significant difference) at 95% confidence level (SAS Inc., Cary N.C.). Data in table 2 marked with the same number and letter(s) are not significantly different. The specific numbers denote specific air quality samples that belong to the same comparison data pool, which are three seasonal data for the two farms. In addition to statistical comparison of the seasonal data of the two facilities, overall average air quality parameters are compared between the two barns. It is found that the average ammonia, odor, and hydrogen sulfide concentrations, indoor temperature, and indoor air velocity of the two barn are not significantly different ($p > 0.05$). However, the average carbon dioxide and total suspended particle concentrations, and relative humidity are statistically significant ($p < 0.05$). In 2004, the weather was rainy, which resulted in high relative humidity. The high relative humidity and wet weather might contribute to the low indoor TSP concentrations.

Seasonal Variations in Air Quality Inside the Dairy Barns

Table 2 also shows that odor concentrations inside the dairy barns were relatively low and there were no significant seasonal variations. Dust concentrations in Barn 1 were not statistically different between March and June but were quite a bit lower than the relatively high dust concentration seen in August. In Barn 2, the dust concentrations were overall very low and not statistically different from month to month. High relative humidity and generally wet weather conditions in 2004 may have contributed to the lower dust levels in Barn 2. Overall, ammonia and hydrogen sulfide concentrations were low as well. Variations existed in some months but not all of the months. Generally, ammonia concentrations were relatively low in March, increased as the temperature increased in June, and then decreased again in August, which may be due to increased ventilation barn sidewall openings and cooling-fan airflow. There were variations in hydrogen sulfide concentrations at different seasons, but no clear trend or pattern. Carbon dioxide concentrations in the dairy barns did not vary significantly from March to August within a year. Due to natural ventilation systems, indoor temperatures had distinct seasonal variations as weather conditions changed from March to August. Indoor relative humidity varied depending on outside weather conditions and indoor temperatures. Indoor air velocity was affected by outdoor wind speed and indoor cooling fans. These cooling fans created statistically high airflow within the dairy barn. As

Table 2. Indoor air quality and environment of the two dairy facilities.[a]

Air Quality Parameters (Ave.± Std. Dev.)	Farm 1 in 2003 March	June	August	Average	Farm 2 in 2004 March	June	August	Average
Odor (OU m^{-3})	105 ±20	79 ±16	117 ±27	100 ±190A	109 ±24	142 ±19	87 ±16	112 ±280A
CO_2 (ppm)	465 ±851a	449 ±551a, b	513 ±1041a	476 ±341A	349 ±591c	379 ±781b,c	366 ±681c	365 ±151B
NH_3 (ppm)	2.1 ±0.52a,b	3.0 ±1.32b,	1.4 ±12b,c	2.2 ±0.82A	0.3 ±0.22c	2.9 ±1.92b	1.3 ±1.22b, c	1.5 ±1.32A
H_2S (ppb)	4 ±73b	12 ±113b	31 ±303a	16 ±143A	26 ±73a	2 ±23b	4 ±23b	11 ±133A
TSP (mg m^{-3})	0.9 ±04b	0.8 ±0.14b	1.5 ±0.14a	1 ±0.414A	0.2 ±04c	0.2 ±0.14c	0.16 ±0.24c	0.2 ±04B
T (°F)	53 ±1.65e	78 ±15c	86 ±15b	72 ±175A	54 ±15d	87 ±0.45a	78 ±0.95c	73 ±175A
RH (%)	79 ±5.46b	54 ±1.76e	57 ±3.76e	63 ±146A	84 ±26a	61 ±3.16d	74 ±2.76c	73 ±126B
Air velocity (m/s)	0.4 ±0.367b	1.4 ±0.77a	1.1 ±0.77a	1 ±0.57A	1 ±0.87a	1.2 ±0.57a	1.2 ±0.77a	1.1 ±0.17A

[a] Data with different superscripts are statistically different by pairwise mean comparison analysis ($P < 0.05$). Specifically, the numbers denote specific air quality parameters that belong to the same comparison data pool; the lower case letters are used to compare air quality in different months; and the upper case letters are used to compare the averages of air quality parameters of the two farms.

Table 3. NIOSH and OSHA indoor air quality standards for occupational health (Donham et al., 2002).

	NH_3 (ppm)	H_2S (ppm)	CO_2 (ppm)	TSP (mgm^{-3})
NIOSH	25	10	5000	4
OSHA	50	20	5000	10

long as the cooling fans were in operation, there were no large seasonal variations in the indoor airflow of the dairy barns.

Particulate Size Distribution in the Dairy Buildings

Figure 3 shows dust size distribution in the dairy barns during the measurements. It is clear that dust size distribution changed temporally. In March, sub-micron particles (0.3-0.5 µm and 0.5-1 µm) were dominant. In June and August, as weather was getting warmer and the cooling fans were in operation, sub-micron particles and fine particles (1-5 µm) increased significantly. The number of medium size particles (5-10 µm) and large particles (>10 µm) were relatively very small. In August when the temperature reached its highest and cooling fans were in full operation, sub-micro particle numbers increased. This is likely caused by small particle re-suspension into the air due to strong turbulent airflow.

Air Quality Spatial Distribution on the Dairy Farms

The upwind location represents background air which is assumed to be free of air contaminants from the dairy. Locations inside of the dairy barn and near the manure holding pond are considered air emission sources. Air quality at 500 ft downwind of the barn represents air to which a neighbor could possibly be exposed. Table 4 shows odor concentrations at the above locations for the different seasons. Values ranged from 33 to 1256 OU m^{-3}. The value for indoor pens is the mean for all points in the barn. The bold numbers indicate a relatively higher level of odor.

It is clear that the dairy barns and manure storage ponds are major odor sources, with the manure storage pond locations presenting the highest odor level on the dairy farms. Odor levels at upwind locations and at locations 152 m (500 ft) downwind of the farm are relatively low in March. However, during special events, odor level at the downwind edge of the manure pond at Farm 1 increased by 16.6 times on windy day in June and by 33 times on manure agitation day in August compared with that in March. Odor generation and dispersion are affected not only by source strength and airflow, but also by weather and geographical conditions. At Farm 2, odor level at 152 m downwind was relatively low in August as well, even though odor concentration at the manure holding pond was similar to that on the June day.

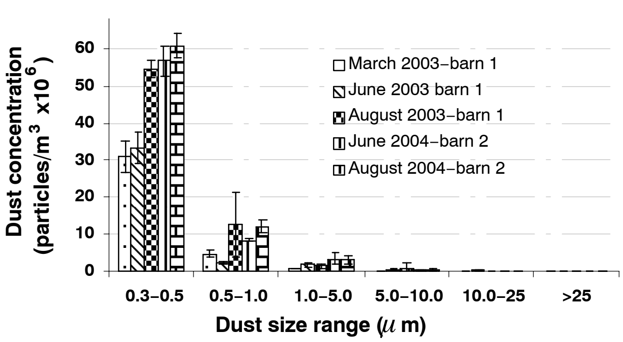

Figure 3. Dust size distribution of the large free-stall dairy barns.

Table 4. Odor concentrations on the dairy farms.

	Odor Concentration (OU m^{-3})					
	Dairy Farm 1			Dairy Farm 2		
Testing Locations	March	June	August	March	June	August
Upwind	17	58	23	47	62	56
Indoor pens	105	79	117	109	141.5	86.5
Manure pond	38	632[a]	1256[b]	67	229	294
Downwind 152 m	33	120	159	79	155	58

[a] Windy day created considerable wave action.
[b] Manure storage was being agitated and emptied.

Odor concentrations inside the dairy barns were fairly stable, averaging levels of 100 OU m^{-3} in all seasons. Odor concentration near the manure holding pond is lower in March, but higher in June and August. For Farm 1, the high wind level in June and manure agitation in August appears to have contributed significantly to the relatively high odor level at the manure storage pond and downwind locations.

Table 5 shows the spatial distribution of ammonia concentration on the dairy farms for the three seasons. It is clear that ammonia is found mostly at the sources of the dairy barn and the manure holding pond. As expected, no ammonia or very low ammonia concentration (<0.5 ppm) was detected at the upwind locations of the farms for all seasons. Average ammonia concentration ranged from 0.5 to 3 ppm for the different seasons inside the barn and 0 to 3 ppm near the manure pond. The ammonia concentration inside the barn was relatively higher in June than in March and August. These results are likely due to the combined effects of ammonia generation in high temperature environments and dilution by the cooling fans. Naturally, higher concentrations of ammonia at the source resulted in higher ammonia concentrations at 61 m (200 ft) downwind of the farm. Since the SPM ammonia analyzer had a 0.5-ppm ammonia measurement resolution, zero (0) ammonia concentration in the table indicates that the ammonia concentration had decreased to less than 0.5 ppm at the 152-m (500-ft) downwind location.

Table 6 shows the dairy farms' spatial distribution of hydrogen sulfide concentration over three seasons. The hydrogen sulfide concentrations ranged from 0 to 1440 ppb. The hydrogen sulfide concentrations at the upwind location were 0 to 5 ppb. The manure storage pond was the major source of hydrogen sulfide air emission. The highest levels of hydrogen sulfide were near the manure storage pond on Farm 1 on both the windy day in June and the manure agitation day in August. Higher source hydrogen sulfide levels resulted in higher hydrogen sulfide concentrations at downwind locations of the farm. At 152 m (500ft) downwind of Farm 1, windy weather conditions resulted in a 23-ppb

Table 5. NH_3 concentrations on the dairy farms.

	NH_3 Concentration (ppm) (Mean ± Std. Dev.)					
	Dairy Farm 1			Dairy Farm 2		
Testing Locations	March	June	August	March	June	August
Upwind	0.0 ±0	0.0 ±0	0.0 ±0	0.0 ±0	0.0 ±0	0.0 ±0
Indoor pens	2.0 ±0.5	3.0 ±1.3	1.4 ±1	0.5 ±0.2	2.4 ±1.9	1.3 ±0.8
Manure pond	1.4 ±0.6	1.5 ±0.3	2.0 ±1.4	0.0 ±0	2.4 ±1.2	3.0 ±0
61 m downwind	0.5 ±0	0.5 ±0	0.0 ±0	0.0 ±0	2.4 ±0.4	0.5 ±0
152 m downwind	0 ±0	0.0 ±0	0.0 ±0	0.0 ±0	0.0 ±0	0.0 ±0

Table 6. H_2S concentrations on the dairy farms.

Testing Locations	H_2S Concentration (ppb) (Mean ± Std. Dev.)					
	Dairy Farm 1			Dairy Farm 2		
	March	June	August	March	June	August
Upwind	0 ±0	3 ±0	5 ±1	1 ±2	0 ±1	1 ±1
Indoor pens	4 ±7	12 ±11	32 ±30	26 ±7	2 ±2	4 ±2
Manure pond	0 ±0	1440 ±458	825 ±35	27 ±17	1 ±1	3 ±3
61-m Downwind	0 ±0	96 ±45	4 ±1	16 ±5	1 ±1	2 ±2
152-m Downwind	0 ±0	23 ±4	0 ±0	8 ±1	0 ±0	1 ±0

hydrogen sulfide concentration, which is still lower than the existing Minnesota state regulatory level of 30 ppb. Management of the large manure pond plays an important role in controlling hydrogen sulfide levels around the dairy farms.

Daily Variation of Gas Concentration Inside the Dairy Barns

Continuous hydrogen sulfide concentration measurement was successfully conducted in March and June in the dairy barn of Farm 2. As an example, figure 4 shows daily variations of hydrogen sulfide concentration in the dairy barn of Farm 2 in June. Hydrogen sulfide concentration fluctuated consistently around mean seasonal values with occasional peaks. The peak concentrations may be associated with manure scraping activities. Analysis of the continuous hydrogen sulfide data showed that the mean daily hydrogen sulfide concentrations were not statistically different from each other for most days of a single month ($P > 0.05$), but were different from month to month ($P < 0.05$). The hourly mean hydrogen sulfide concentrations within each day were not statistically different.

Continuous ammonia concentration measurements were successfully conducted in June and August of 2004 in the dairy barn of Farm 2. For example, figure 5 shows the hourly mean ammonia concentration in the dairy facilities in June. Analysis of the six-day continuous ammonia data showed that the daily, daytime (0900 to 1700 h), and nighttime (2000 to 0800 h) mean ammonia concentration are statistically different from each other ($P < 0.05$). In June, the ammonia concentrations fluctuated with peak concentrations in the morning, evening, and midnight hours. These peak points are jointly affected by indoor air temperature and barn ventilation rate. High air temperature is likely resulted in high ammonia concentration. High barn ventilation rate will

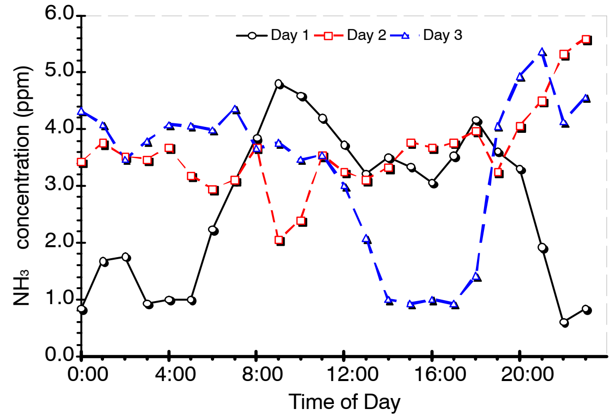

Figure 5. Daily variation of ammonia concentration in dairy Farm 2 in June 2004.

decrease barn ammonia concentration. In August, ammonia concentrations were relatively low and peak concentrations during the daytime were only observed around noon, with readings of 3.4 and 1.1 ppm during the 1st and 2nd day, respectively. The hourly mean ammonia concentrations with in a day were not statistically different between the early-morning hours (2400 to 0600 h), the morning hours (0900 to 1200 h), and afternoon hours (1300 to 1700 h).

Continuous CO_2 concentration measurements were also successfully conducted on three separate days during March, June, and August in the dairy barn of Farm 2. Figure 6 shows examples of daily variations of CO_2 concentration in the dairy barn of Farm 2 during August 2004. CO_2 concentrations fluctuated more widely in the nighttime (2000 to 0800 h) than in the daytime. Statistical analysis of continuous CO_2 data showed that the daily (0000 to 2400 h) and nighttime (2000 to 0800 h) mean carbon dioxide concentrations were statistically different for most days ($P < 0.05$) and daytime (0900 to 1700 h) mean CO_2 concentrations were not statistically different for most days in a month ($P > 0.05$), but the daytime means in June were significantly higher than in March and August. CO_2 concentrations range from 340 to 390 ppm in March and 490 to 562 ppm in June. Most daytime hourly mean CO_2 concentrations with a day were not statistically different on measurement days in March and August and showed more difference on measurement days in June. Most nighttime hourly mean CO_2 concentrations within a day were statistically different in June and August

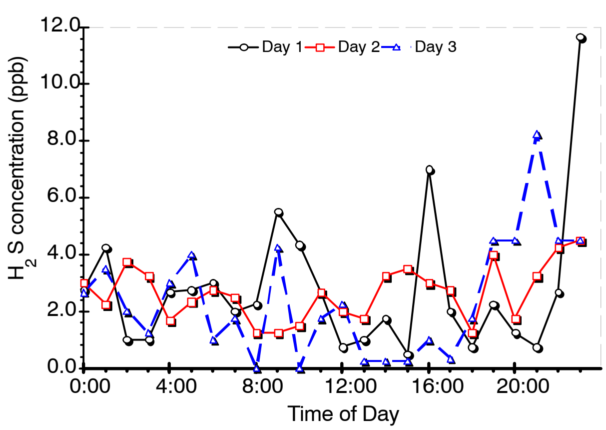

Figure 4. Daily variation of hydrogen sulfide concentration in dairy Farm 2 in (a) March and (b) June of 2004.

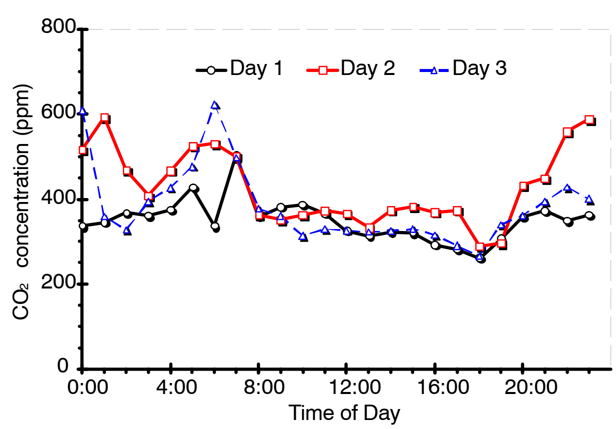

Figure 6. Daily variations of indoor carbon dioxide concentrations in dairy Farm 2 in August 2004.

and not statistically different in March. The significantly variant hourly means occurred at peak concentrations ranging from 400 to 600 ppm, which occurred mostly near midnight of each day.

Conclusions

Air quality inside new large dairy buildings is acceptable in comparison with OSHA and NIOSH indoor air quality standards. Inside the free-stall dairy barns, the average ammonia concentration ranged from 0.3 to 3 ppm; the average hydrogen sulfide concentration ranged from 2 to 31 ppb; the average dust concentrations were 1.1 mg m^{-3} inside the barn at Farm 1, but 0.2 mg m^{-3} inside the barn at Farm 2. The average odor concentrations inside the dairy barns ranged from 79 to 141 OU m^{-3}.

Additionally, spatial variations of indoor air quality within the new dairy buildings were very limited probably due to low air emission rates and natural ventilation systems.

Indoor thermal environments were strongly affected by weather conditions and thus had clear seasonal variations. Indoor airflow had no significant variations for most warm months due to cooling fans. Dust concentrations in Barn 2 had no seasonal variations due to wet weather, but dust concentration in Barn 1 saw higher levels in August. Dust size distribution varied temporally. Daytime CO_2 concentration measurements showed no variation among the three measurements in the different months at each facility. Hydrogen sulfide concentrations did vary, but with no clear trend. Ammonia concentration also varied among the measurement months with June showing the highest values.

Gas and odor emissions disperse significantly along the downwind direction. Consistently, ammonia concentrations at 152 m (500 ft) downwind of the dairy farms were lower than 0.5 ppm. Odor concentrations at 152 m downwind of the farms became higher only when considerably high concentrations occurred at the manure storage ponds in June and August. Higher hydrogen sulfide concentrations at the manure pond also caused higher concentrations of this gas at 152 m downwind of the dairy farm. However, hydrogen sulfide levels at 152 m downwind did not surpass 30 ppb on any of the measurement days, including during manure agitation and on windy days.

Inside the buildings, the daily mean hydrogen sulfide concentrations were statistically different among days in different seasons, but not significantly different for most days within a season and for most hours within a single day. However, daily mean, daytime mean, and nighttime mean ammonia concentrations were significantly different among most of the test days. Hourly mean ammonia concentrations, though, were not significantly different between early morning hours, morning hours, and afternoon hours during a single day. As for carbon dioxide, daily mean and nighttime concentrations did differ significantly among most of the days. However, daytime mean CO_2 concentrations were not much different on most days in month. Nighttime hourly mean CO_2 varied significantly in June and August, except for in March. Daytime hourly mean CO_2 concentrations were not statistically different during measurement days except for in June.

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